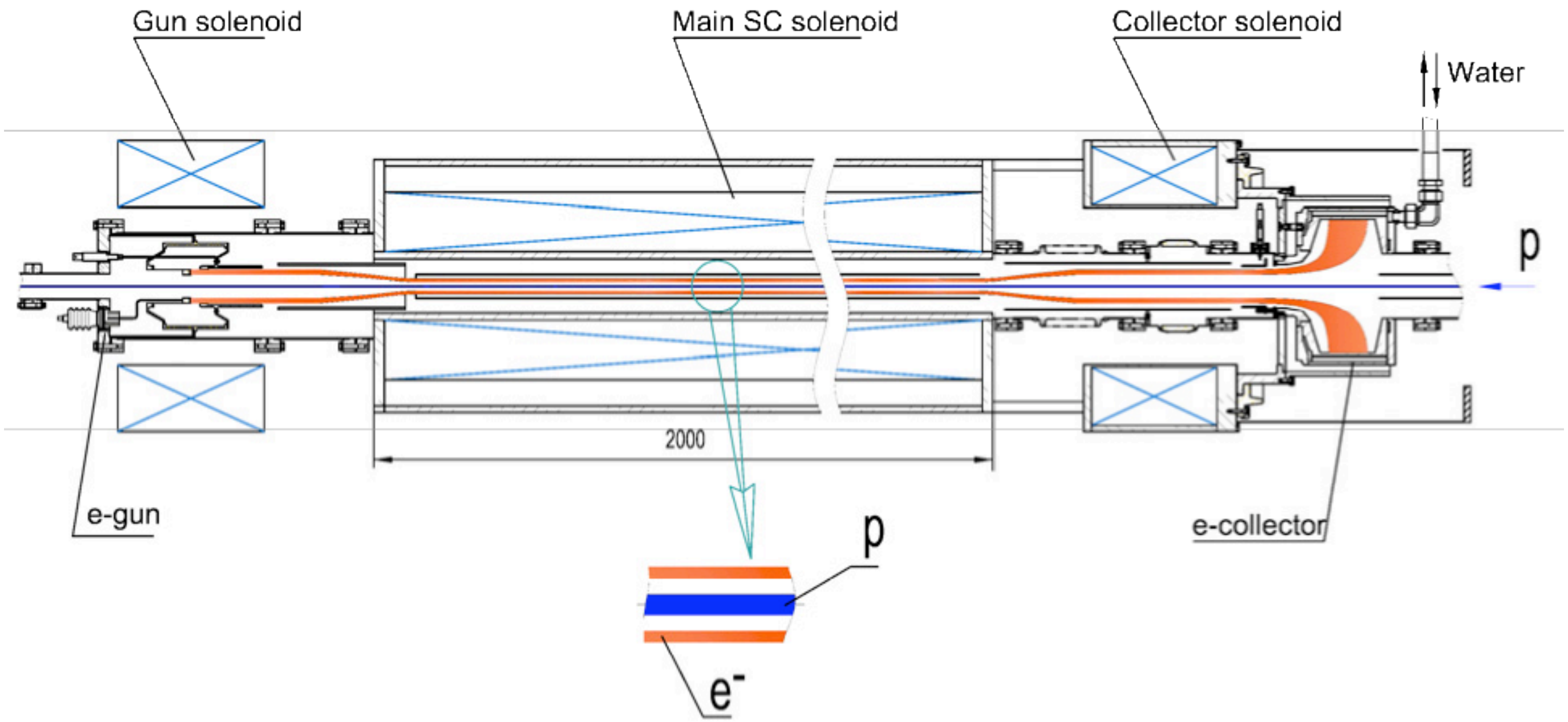
US LHC Accelerator Research Program

BNL - FNAL- LBNL - SLAC

Hollow e-Beam Lens for LHC Scraping



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Motivation

- As of now, there are no beam scrapers in the LHC
- We have low Z graphite primaries at 6 sigma, then secondaries at 7 sigma
  - No material can survive closer than 5 sigma
- It would be great if we could have a beam scraper with a smaller radius to help remove (increase the dispersion rate) of halo particles. “Clean out” beam halo.
  - Electron beam is indestructible, No direct interaction with material
- Could be used to eliminate loss spikes due to shaking beam.
- Increase the impact parameter of primaries
- May allow for the primaries to be pulled out to greater sigma.
- Electron lenses have been used for some time with much success at Fermilab. Clean abort gap, Beam-Beam compensation, increase beam lifetime
- The idea would be to turn one (or more) on just long enough to clean out the beam halo. Repeat as many times as necessary.
- Could also be used for ion collimation

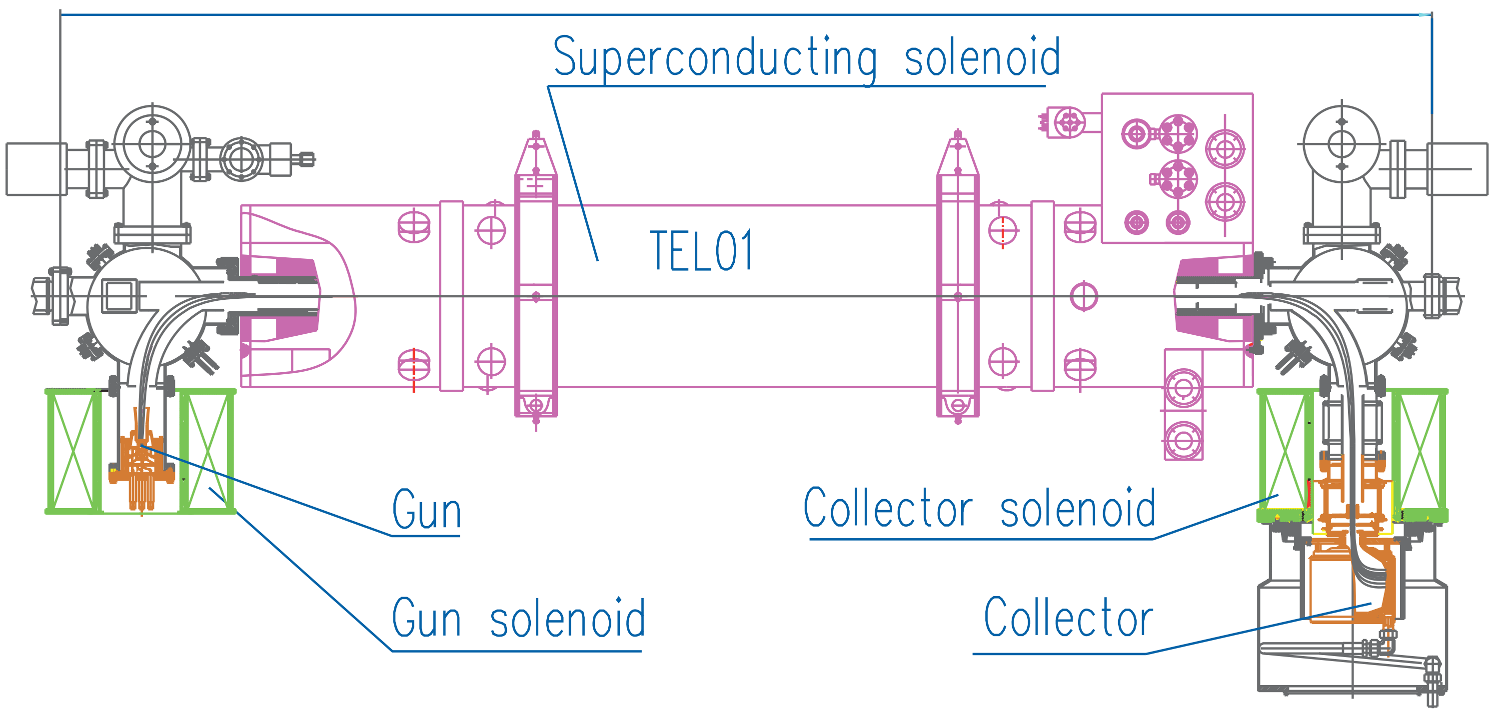
Previous work

- Work based on:
  - V. Shiltsev, *et al.*“LHC Particle Collimation by Hollow Electron Beams,” EPAC08, MOPC098
  - V. Shiltsev, “Electron Lenses For Particle Collimation in LHC,” FERMILAB-CONF-07-698-APC
  - V. Shiltsev, *et al*. “Tevatron electron lenses: Design and operation,” PRST AB **11**, 103501 (2008)
    - Some results presented are from these papers.

Basics of an Electron Lens

- An electron lens is a very stable thin, long very straight cylinder of electrons with kinetic energy around 5 to 10 keV.
- The lens is controlled with a ~3 Tesla longitudinal (solenoidal) magnetic field.
- The electric field established by the electrons is roughly 0.3MV/m radially which can attract passing protons.

Tevatron Electron Lens 1 diagram



Tevatron Electron Lens 1 in tevatron

Hollow Electron lens

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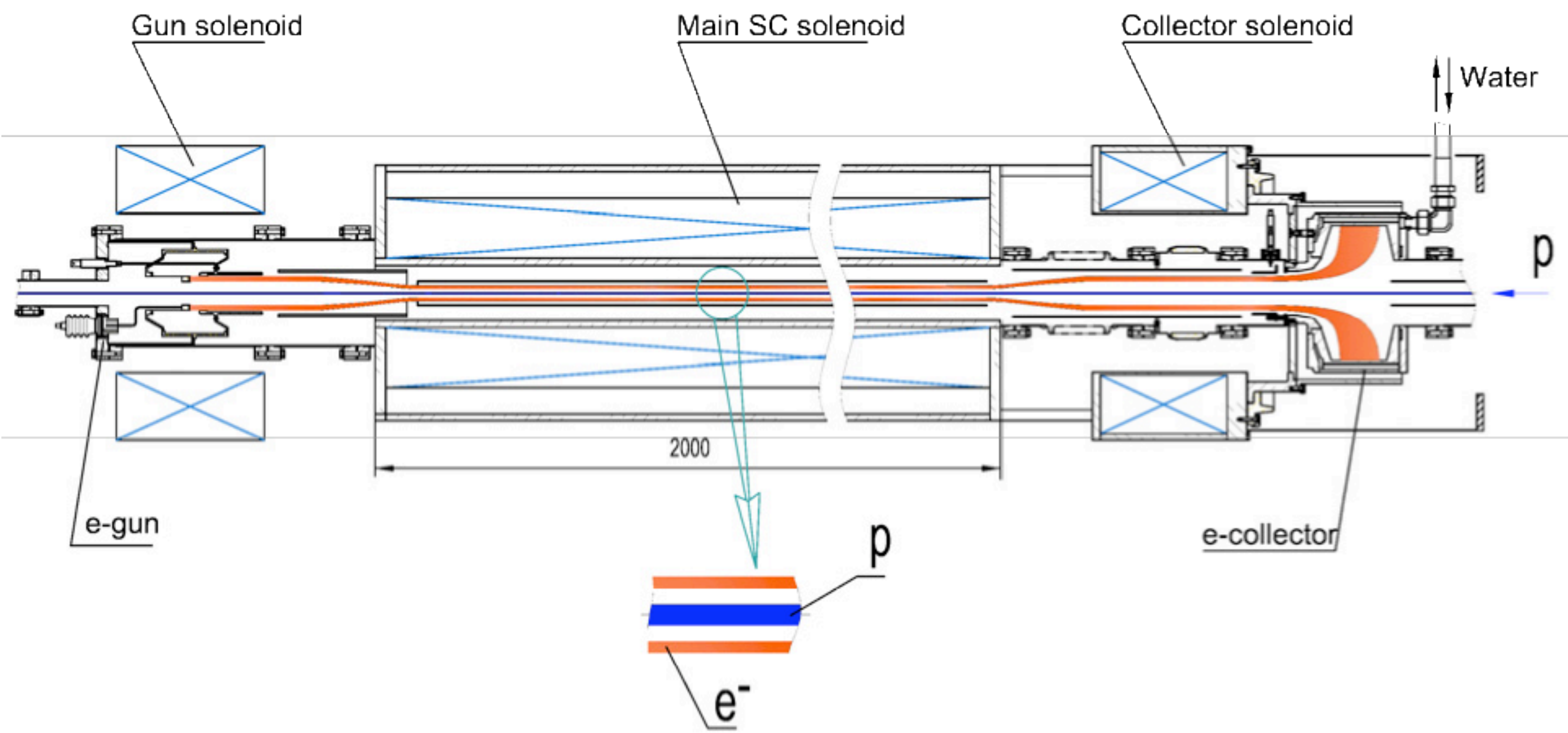
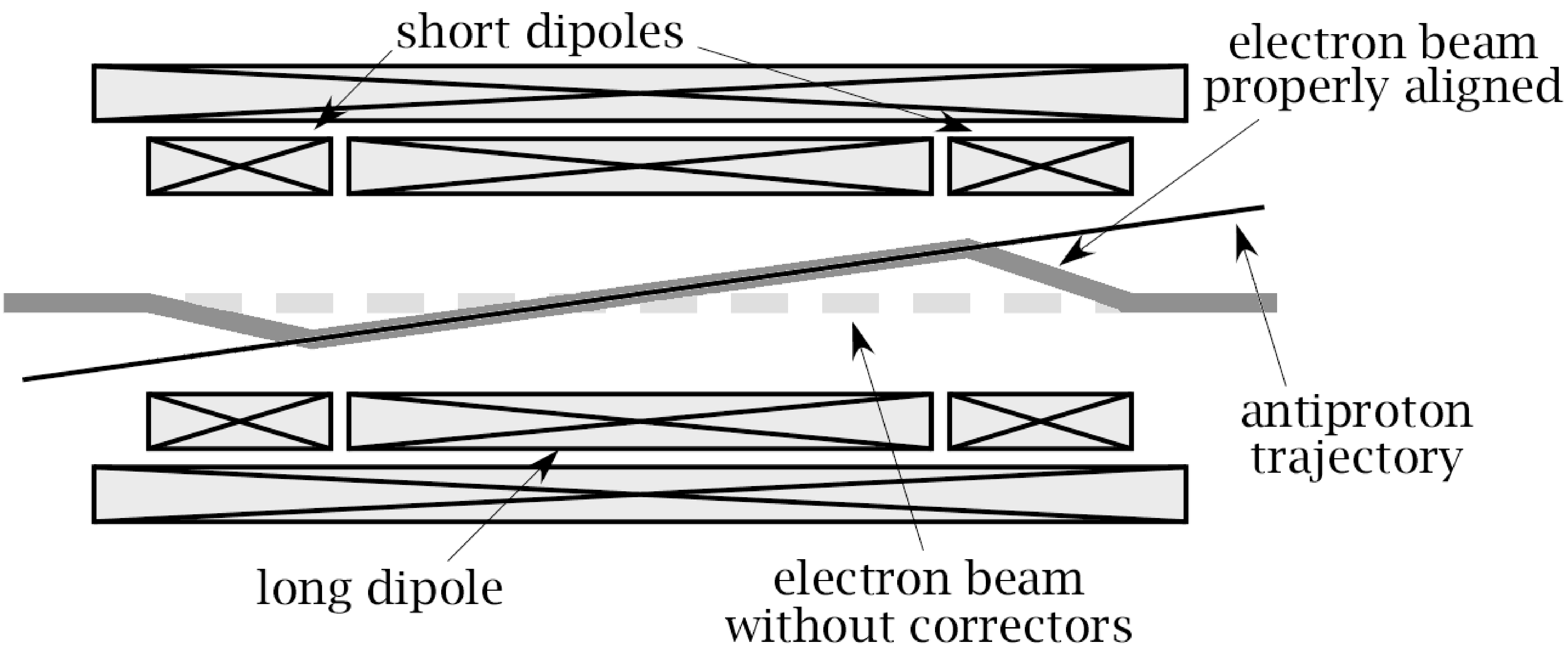
- A Hollow Electron Lens is a hollow cylinder of electrons.
- Inside the cylinder there is no electric field and so particles experience no kick
- Within cylinder and outside particles experience a kick

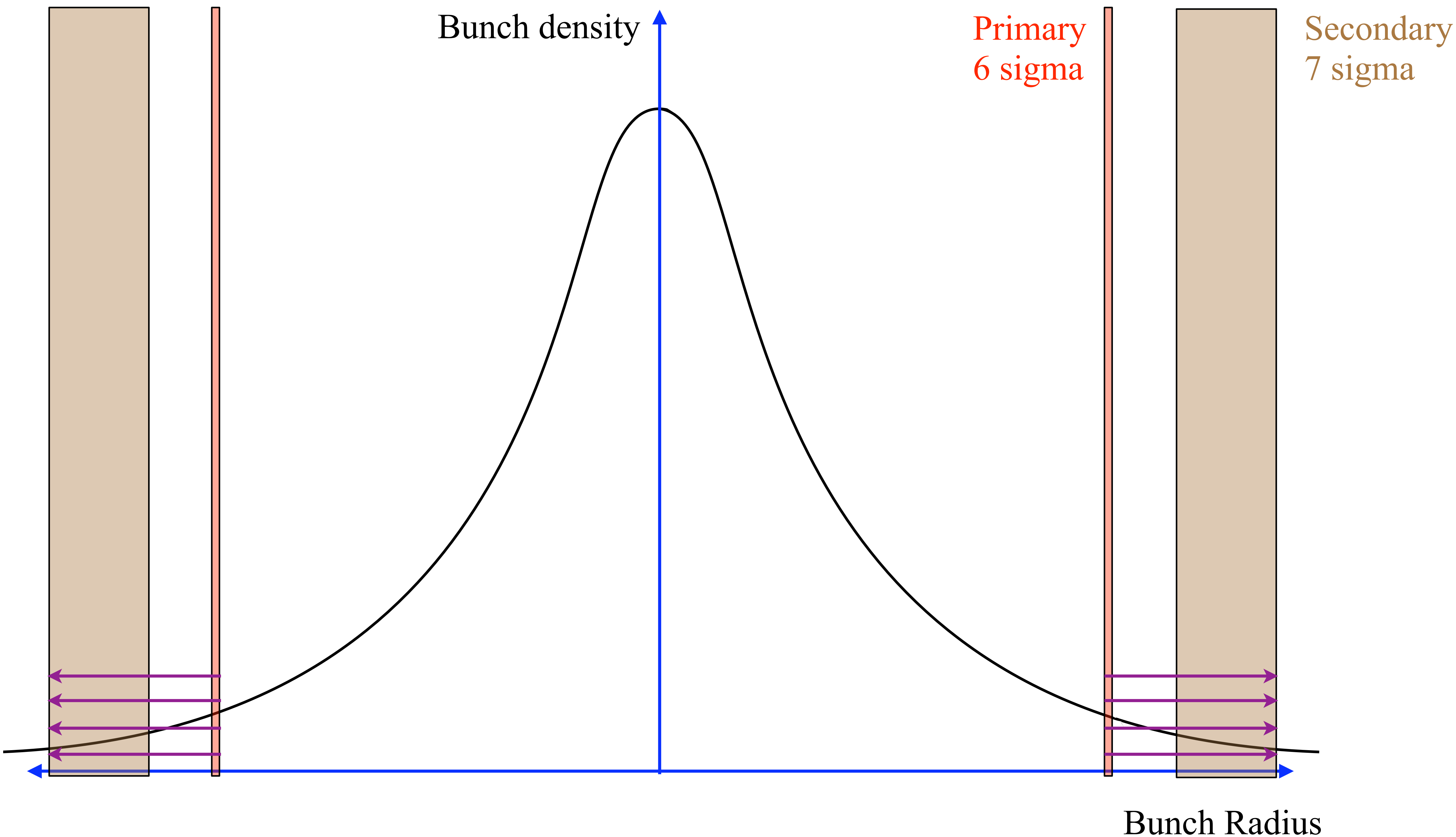


E-Beam steering

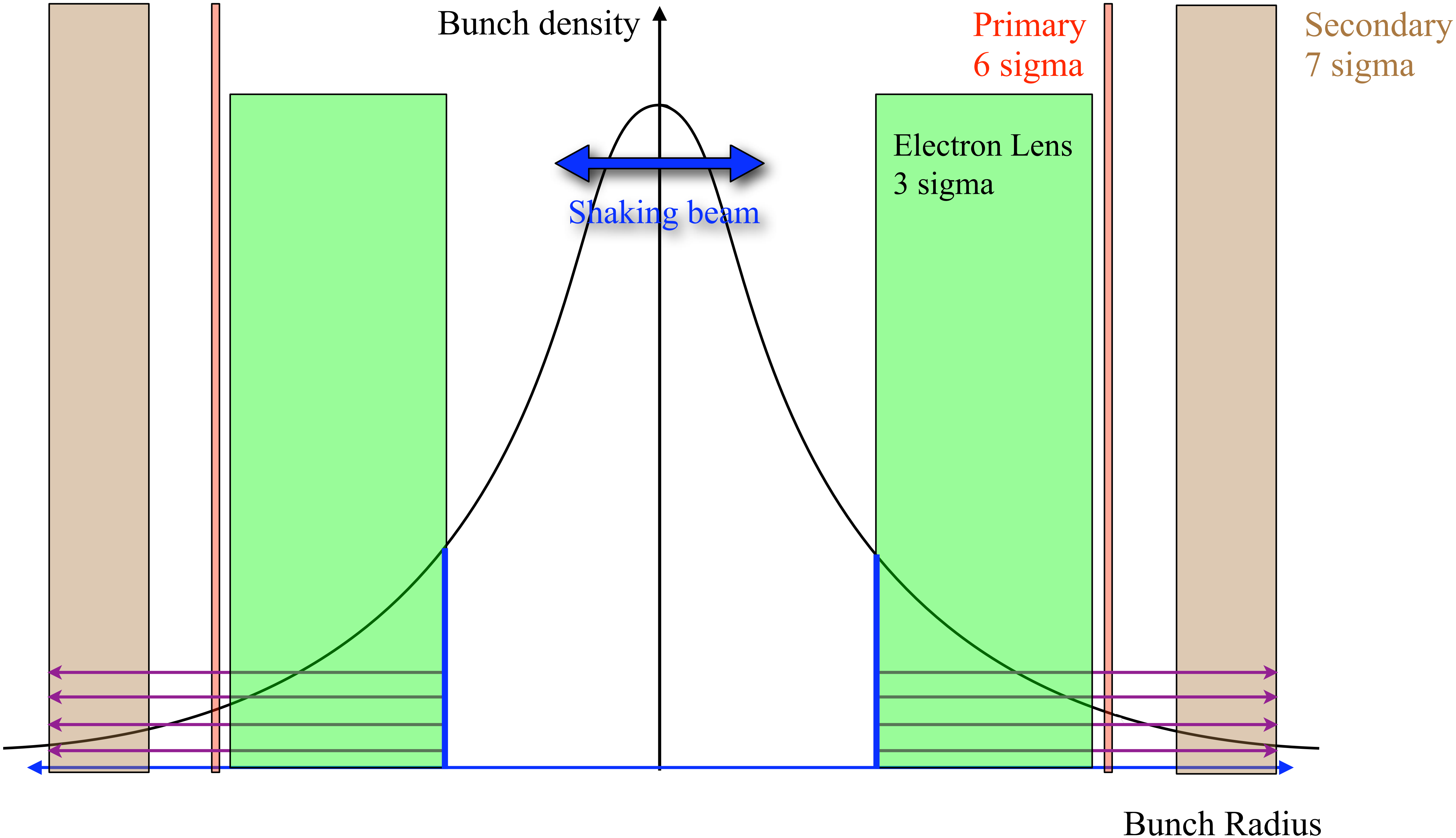
- Steering of the electron beam is controlled by several dipole coils along the length of the interaction region
  - ~ 40 mm, 30 mrad deflection of e-beam
  - Radius of e-beam also controllable



Current LHC Collimation System



With Hollow Electron Beam Scraper



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Bunch Distribution

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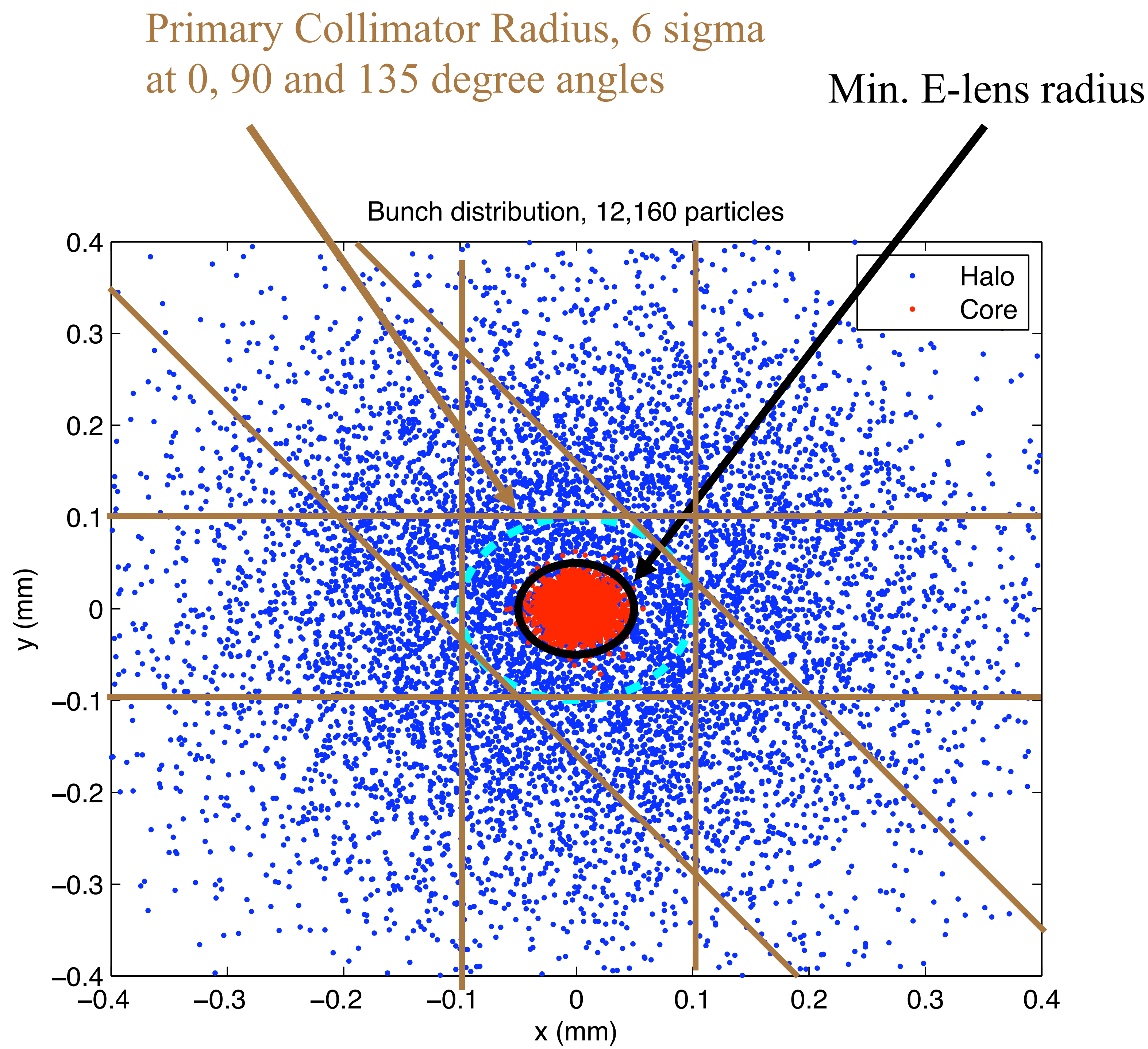
- Can model with two Gaussian distributions
  - Core population at nominal emittance
  - Halo populated at 100 times emittance (10x sigma)
  - Halo populated 3 times as much as core
- Everything outside the Primaries should get absorbed within a couple turns
- Between the Electron Lens and primaries is what we are really looking at.
- Beam heating works on a much longer time scale than collimation

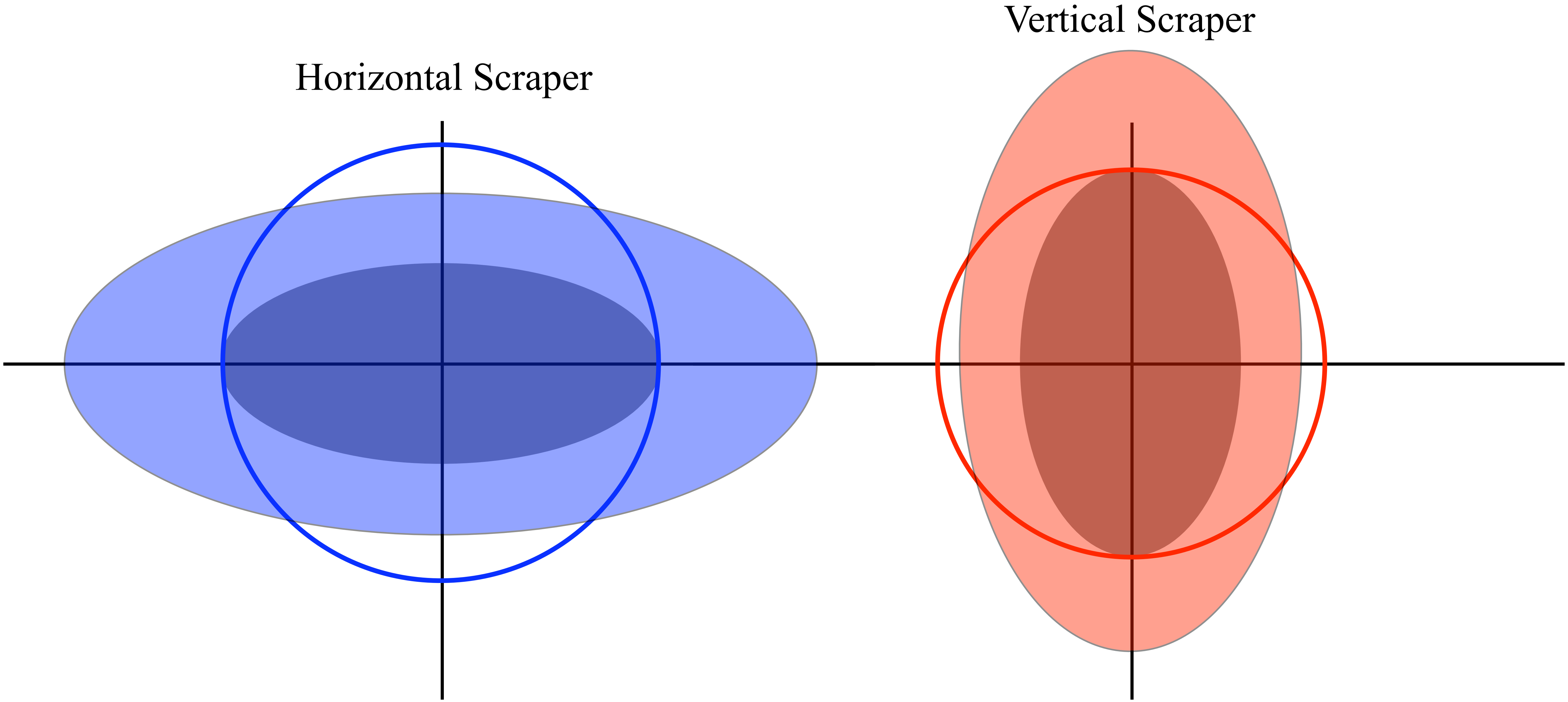


Location of Electron Lens

- There are 6 TCHS scraper locations available.
  - Beta_x, Beta_y ~ 100 m
  - 3 sigma ~=> 0.7 mm
  - OK, but small for a e-lens
- There are also BBC elements that could fit an e-lens
  - Beta_x = Beta_y ~ 1750 m
  - 3 sigma ~=> 3 mm
  - Much easier to make e-lens
- Electron Lens Parameters:
  - Length = 1-2 meters
  - Inner diameter = 3.0-4.0 sigma
  (absolute diameter depends on beta function at location: 0.7 mm - 3.7 mm)
  - Beam width: a few sigma (a few millimeters)
  - Current = 10-100 Amps
  - Beam power = 20 - 50 kW
  - These are acceptable electron lens parameters and not unlike those already used at Fermilab
  - Maximum kick with these parameters ~ 0.2 urad
    - Small compared to 4.5 urad kick of primaries but can act over many turns.

Round Electron Lens

- The electron lens can only be round. Beta-x and beta-y should therefore be ideally equal. True at BBC elements but not at scraper locations
- Two e-lenses, one for horizontal and one for vertical.

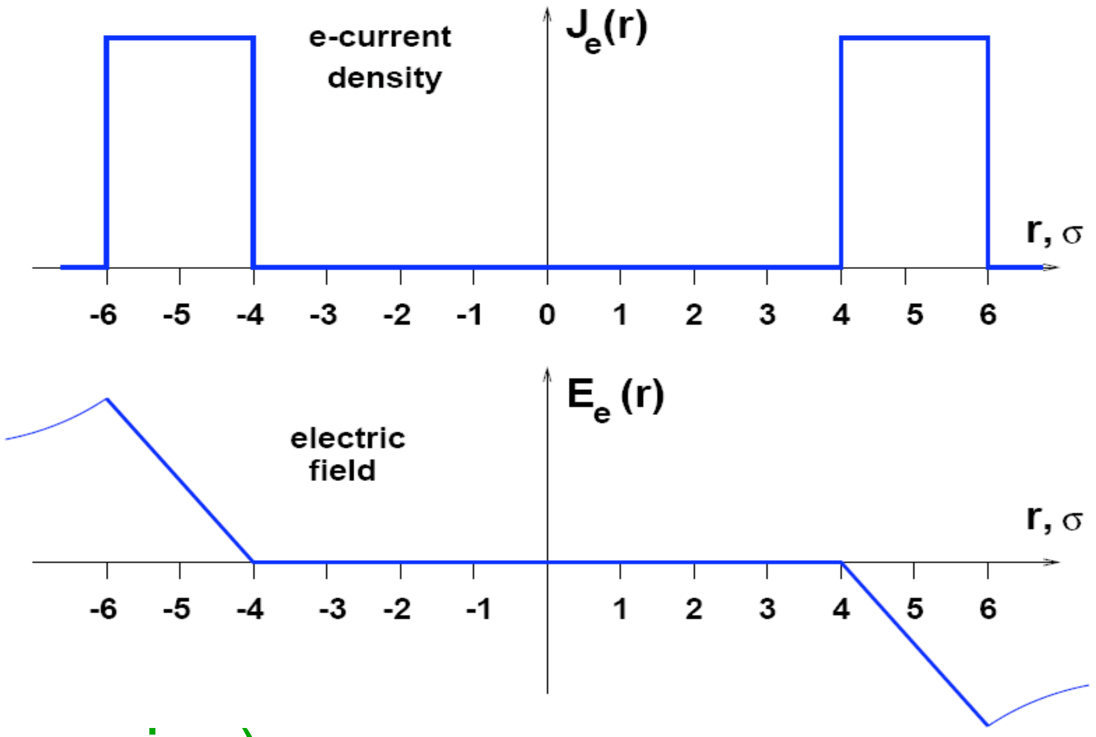


Electron Lens Model

- Using simple model. Just an E-field produced by the electron beam as a thin lens. No scattering just interaction with E-field

$$\Theta(r) = \Theta_{max} \begin{cases} 0, & \text{if } r < r_{min}; \\ \frac{r - r_{min}}{r_{max} - r_{min}}, & \text{if } r_{min} < r < r_{max}; \\ \frac{r_{max}}{r}, & \text{if } r > r_{max}. \end{cases}$$

$$\Theta_{max}\,[\mu rad] = \frac{0.2L[m]J[A]}{(B\rho)\,r_{max}} \cdot \frac{1+\beta_e}{\beta_e}$$



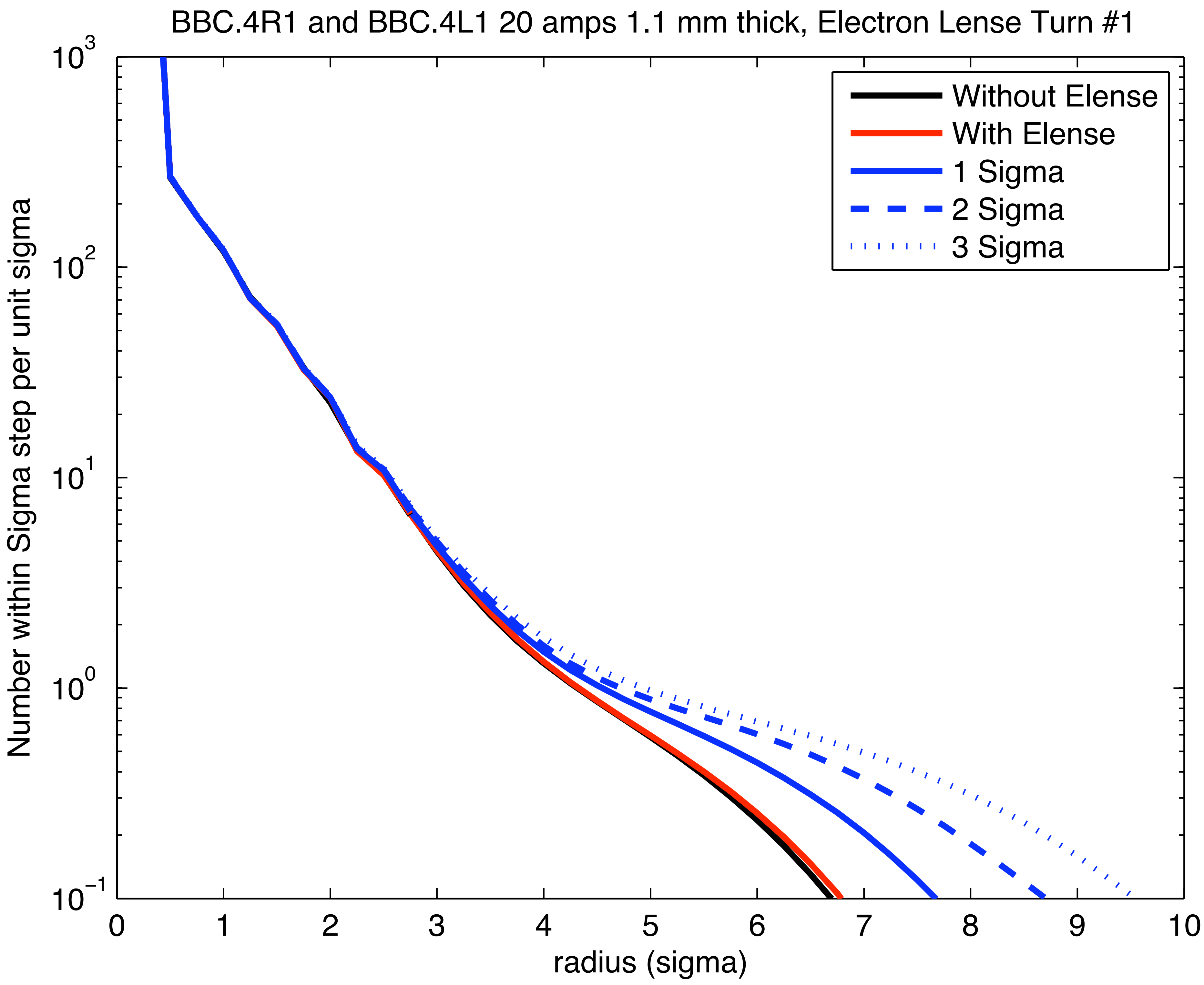
- This is a very simple model
  - Should include:
    - More realistic field distribution (Gaussian)
    - Field errors

Summary of E-lens Studies in Sixtrack

- With practical DC current e-lens parameters, found to remove beam halo in about
  - 1500 turns ~ 130 milliseconds, without Collimators
  - <1000 turns with Collimators at 6,7 sigma
- E-lens at 3 sigma is rather close and scraping of the beam core is evident. 4-sigma is a much “safer” radius.
- By increasing the Halo particle diffusion rate, the impact parameter on the primaries should increase, thereby increasing collimation efficiency.
  - Effects on collimation efficiency to be studied
  - Even if doesn’t increase efficiency rate, it can still be used as a scraper

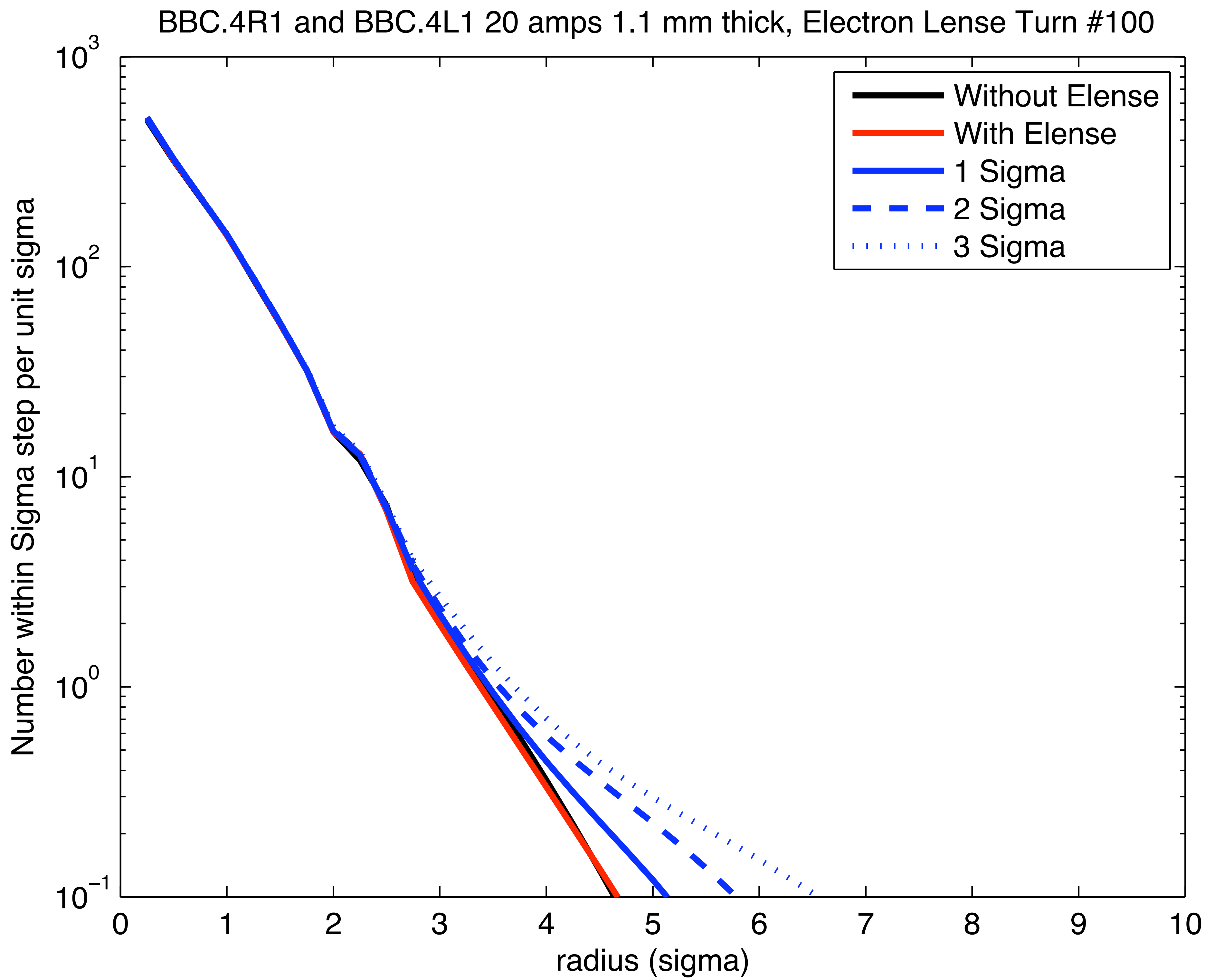
Example: two BBC

- Turn #1
- Here the beam profile is plotted in four cases:
    1. Nominal phase I collimation system
    2. Electron lens added
    3. Electron lens but with primary and secondary collimators pulled out by 1 sigma
    4. ...pulled out by 2 sigma
    5. ...3 sigma
- Beam halo overpopulation clearly evident to make measurement of effect possible



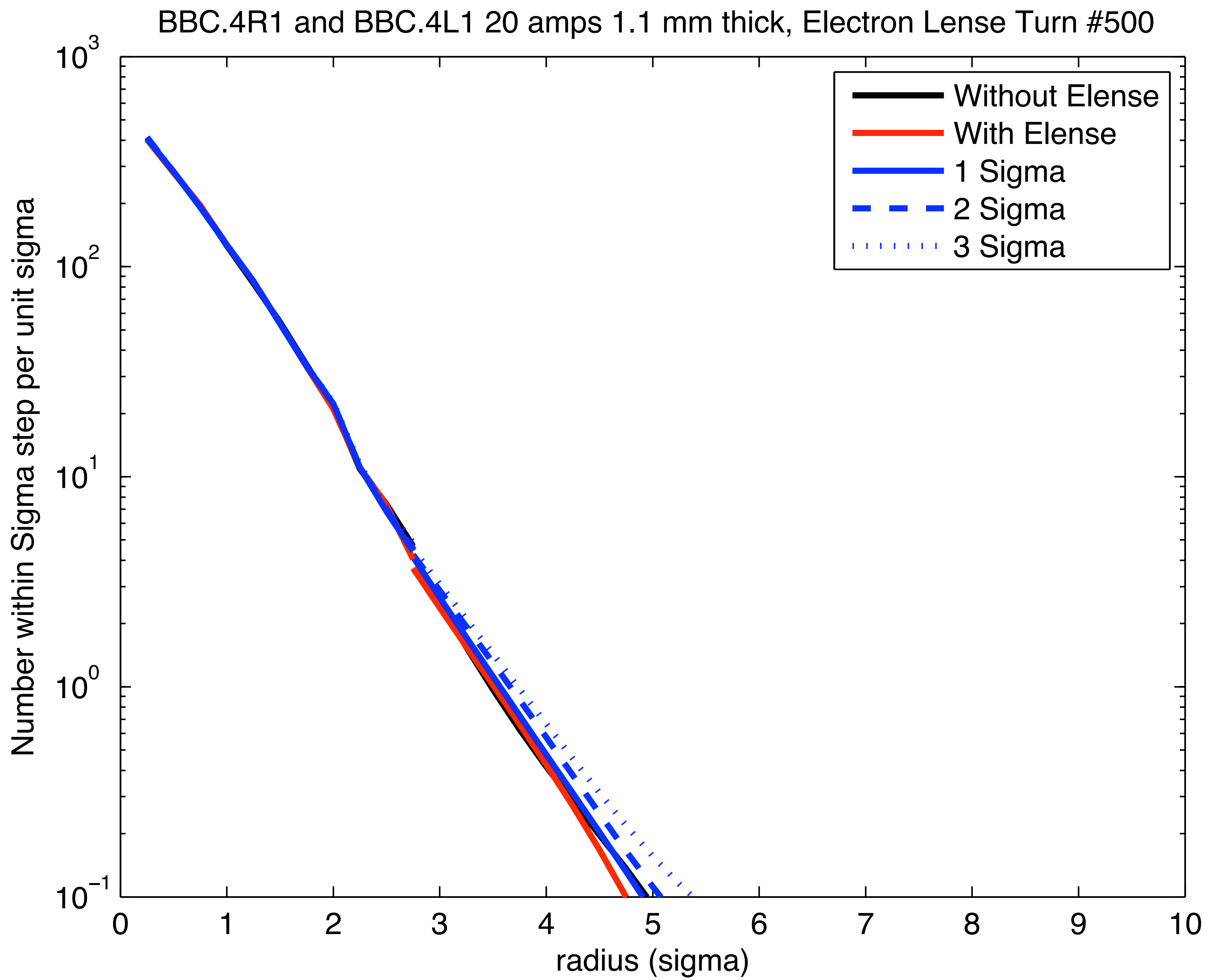
Example: two BBC

- Turn #100
- Note red curve and that nominal collimation system removing beam halo well within 100 turns



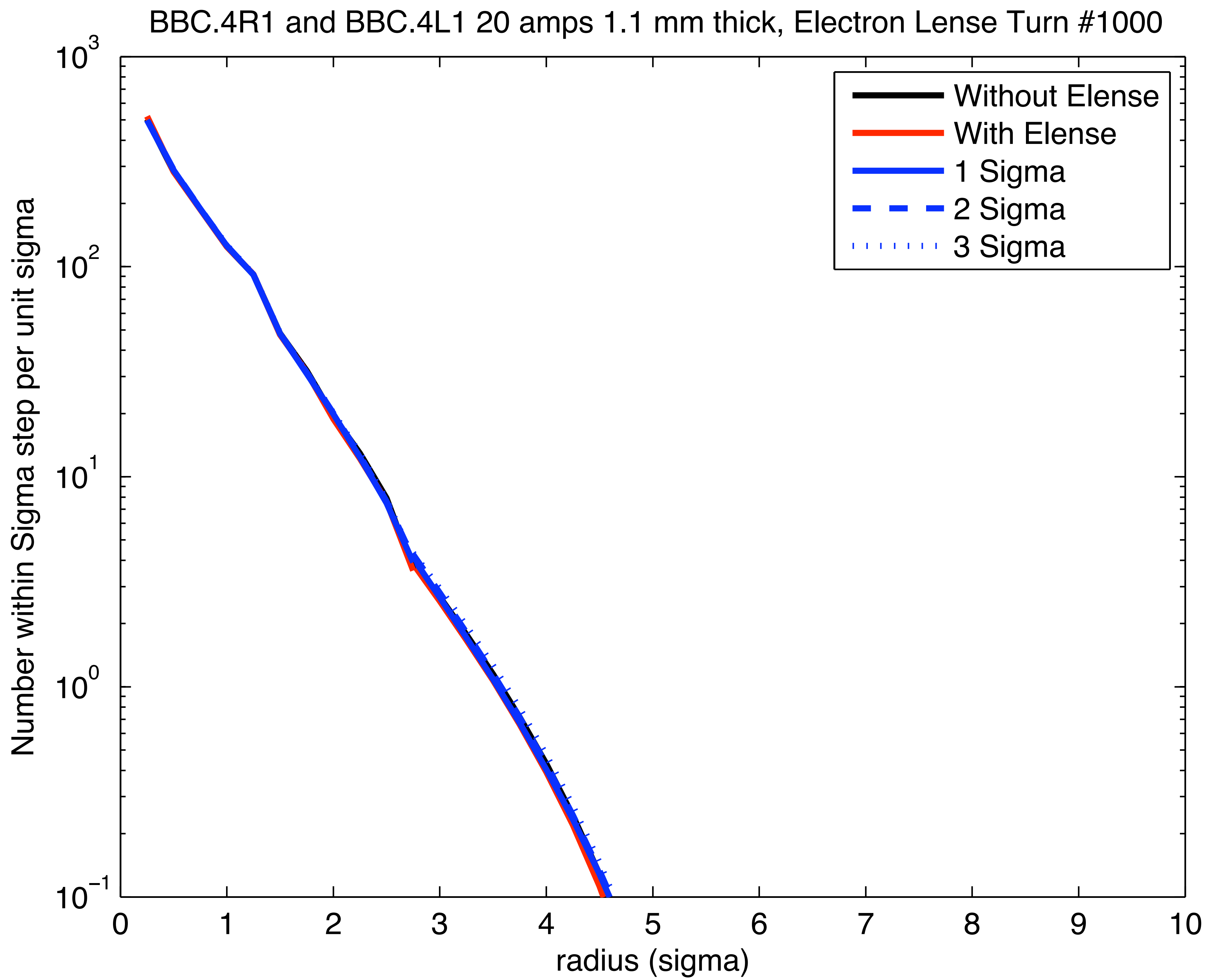
Example: two BBC

- Turn #500



Example: two BBC

- Turn #1000
- Within 1000 turns system the same as if primaries were at nominal (6 sigma)



AC Current

- Additional resonance effect is possible with modulating the E-Lens current with the Betatron frequency of the beam.

$$\begin{pmatrix} x \\ \dot{x} \end{pmatrix} = \begin{pmatrix} \cos 2\pi Q & \sin 2\pi Q \\ -\sin 2\pi Q & \cos 2\pi Q \end{pmatrix} + \begin{pmatrix} 0 \\ \theta_{elens} \end{pmatrix}$$

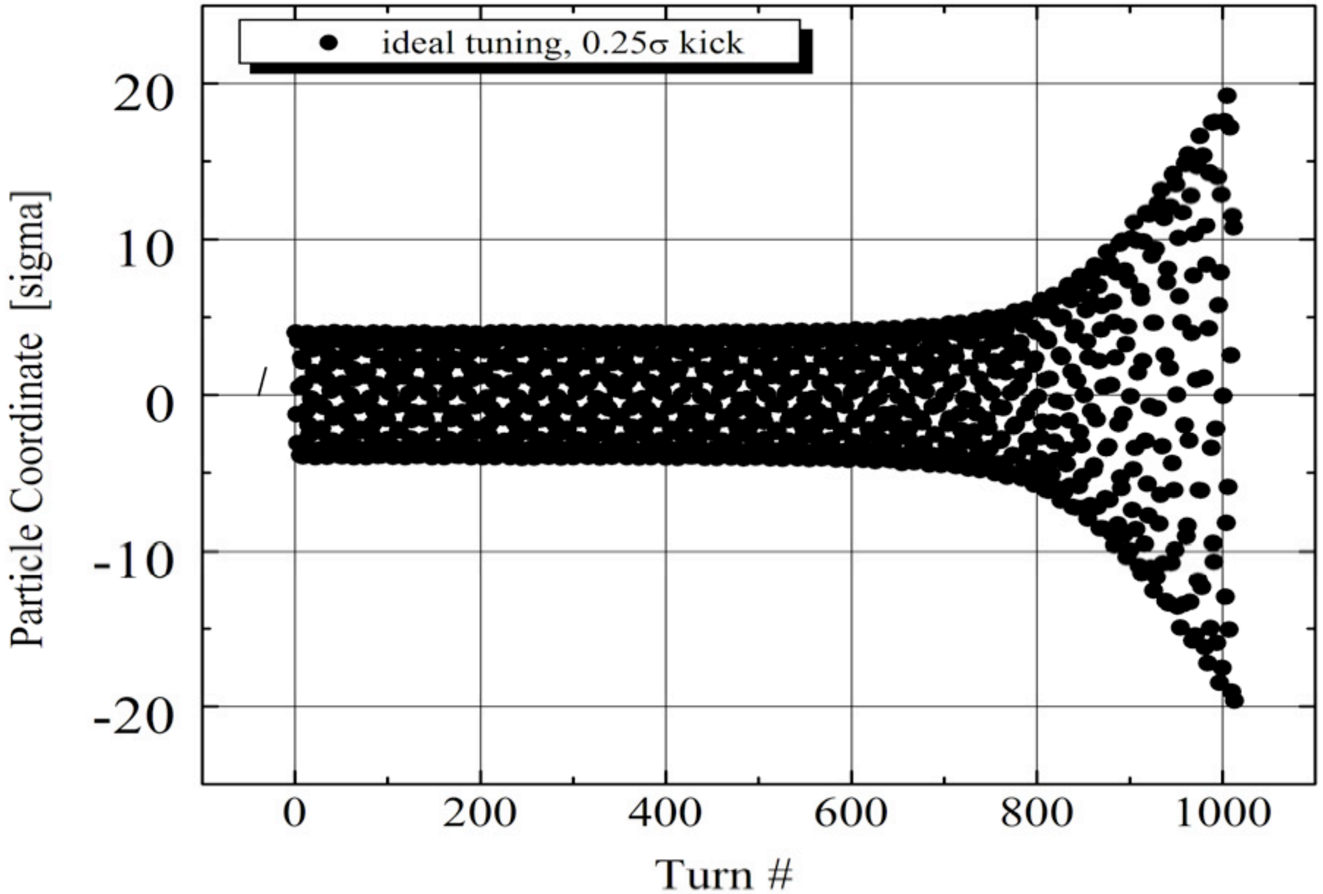
$$\dot{x} = -x \sin 2\pi Q + \dot{x} \cos 2\pi Q + \theta \cos(\omega t + \psi)$$

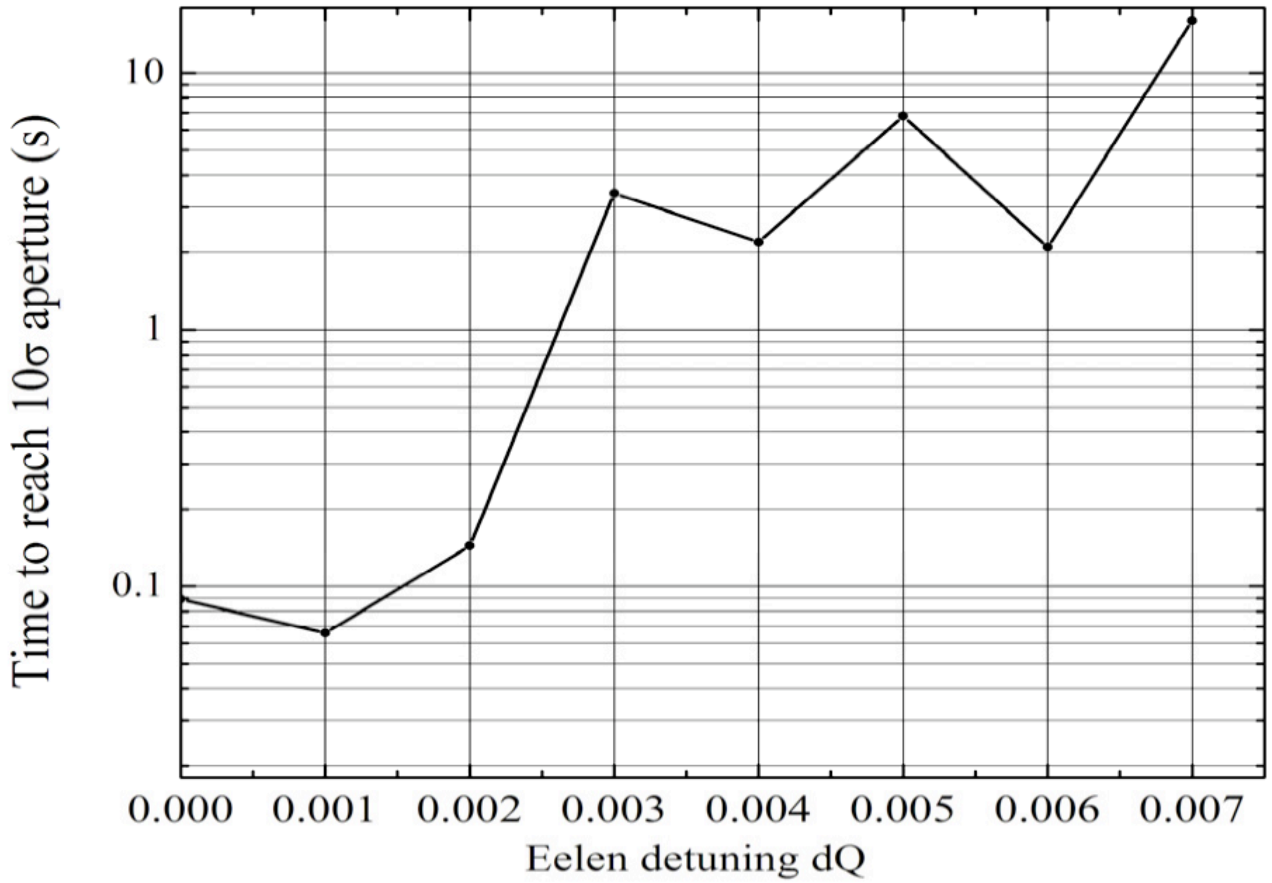
$$\text{resonance when: } 2\pi Q = \omega t + \psi$$

- Studies by Valdimir Shiltsev and Alexander Drozhdin at FNAL have shown potentially an order of magnitude faster cleaning time.
- The DC effect is quite evident, but AC beam may improve performance much more.
  - Being investigated in Sixtrack with realistic beam

Performance vs E-lens Modulation

- From EPAC08 MOPC098
- Single particle motion
- Factor 100 improvement in time!
  - Of course, this is only for on-tune particles. In reality there will be a rather large tune spread, especially for the large amplitude halo particles.
  - Nevertheless, this will be included in future Sixtrack studies.





LHC Beam Tune Spread

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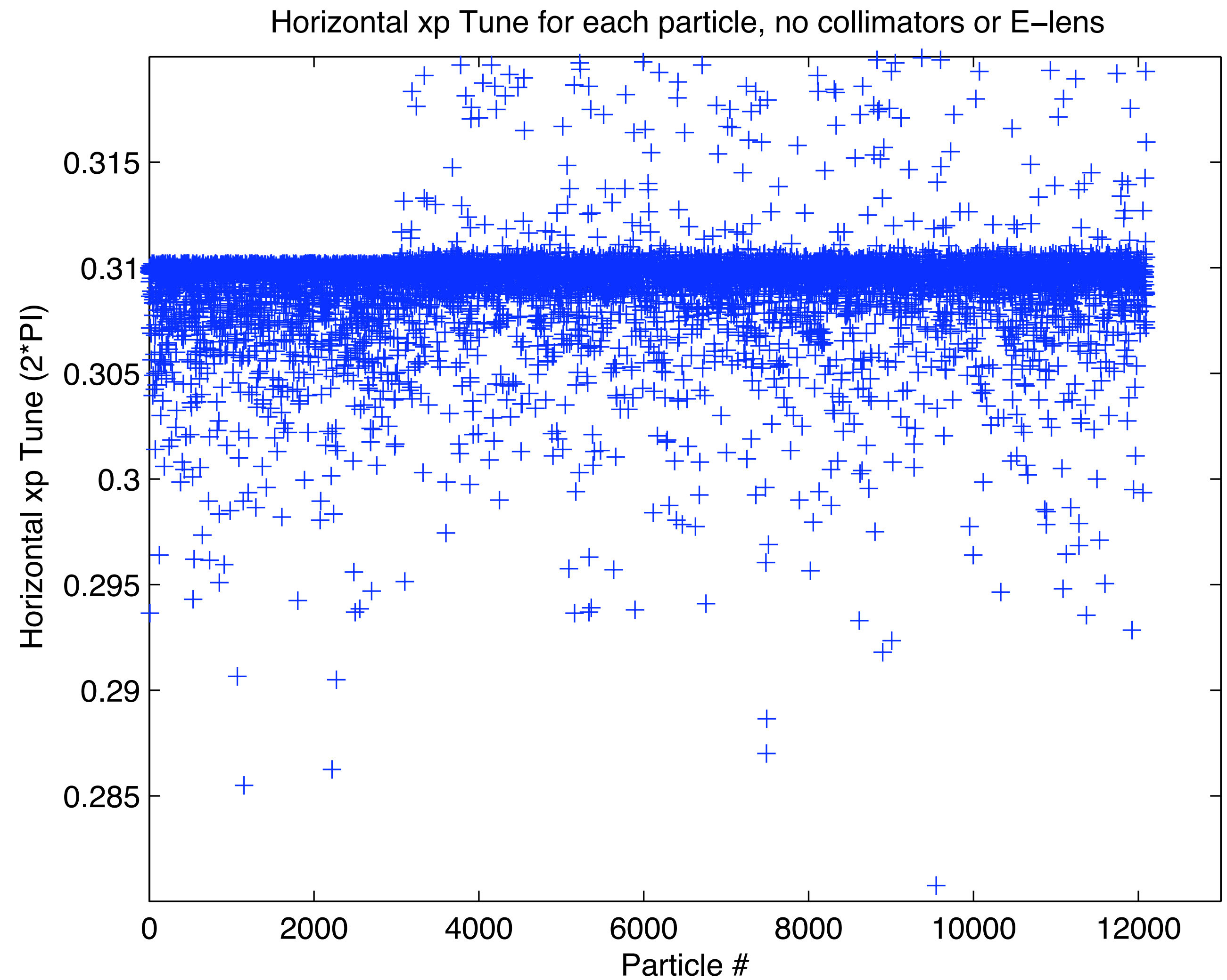
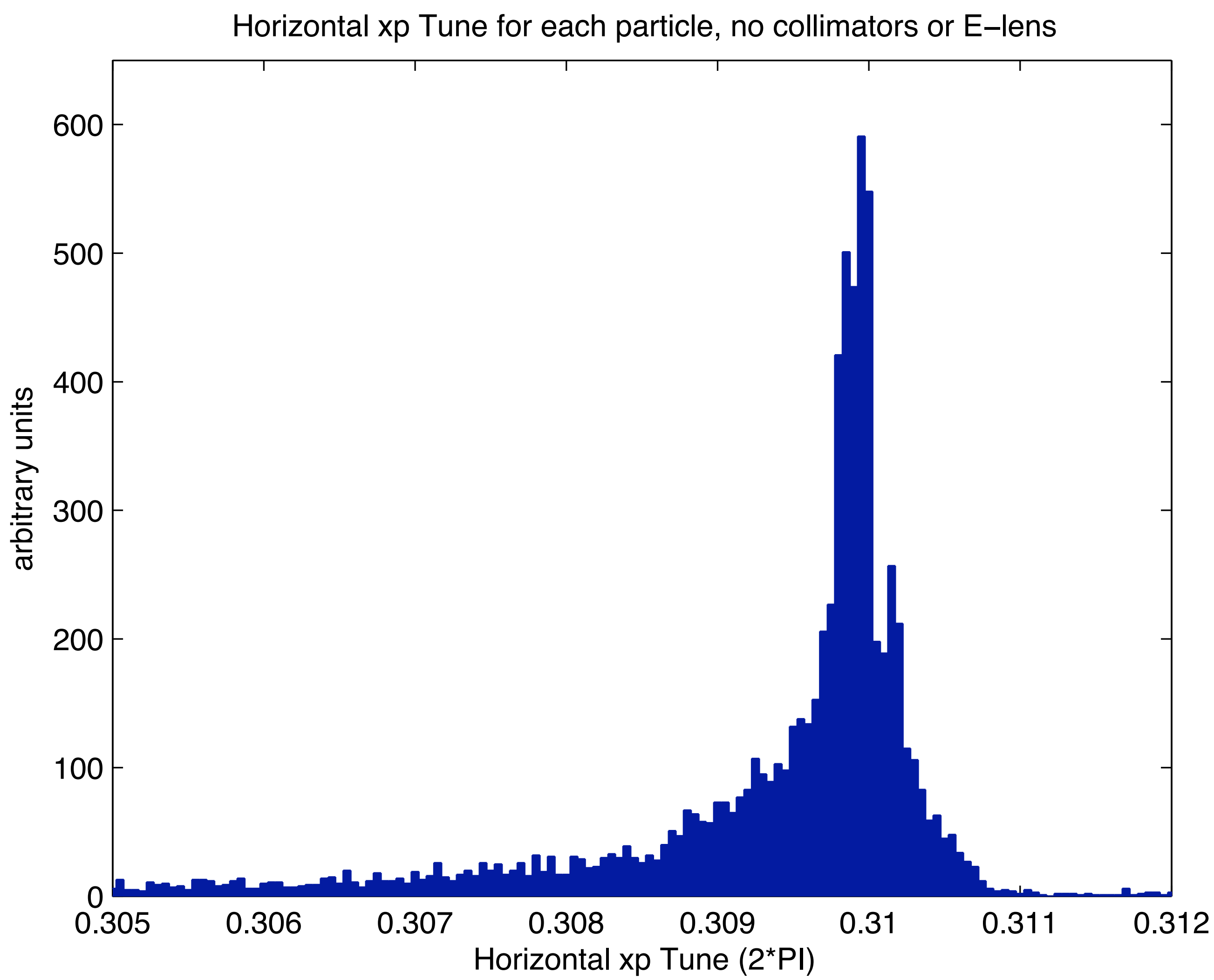
- Tune spread for beam halo is about dQ = 0.001 (agrees with simple tune shift formula)
- Acceptance for resonance condition is about dQ = 0.002 (see previous slide)





Tune Shift due to E-Lens

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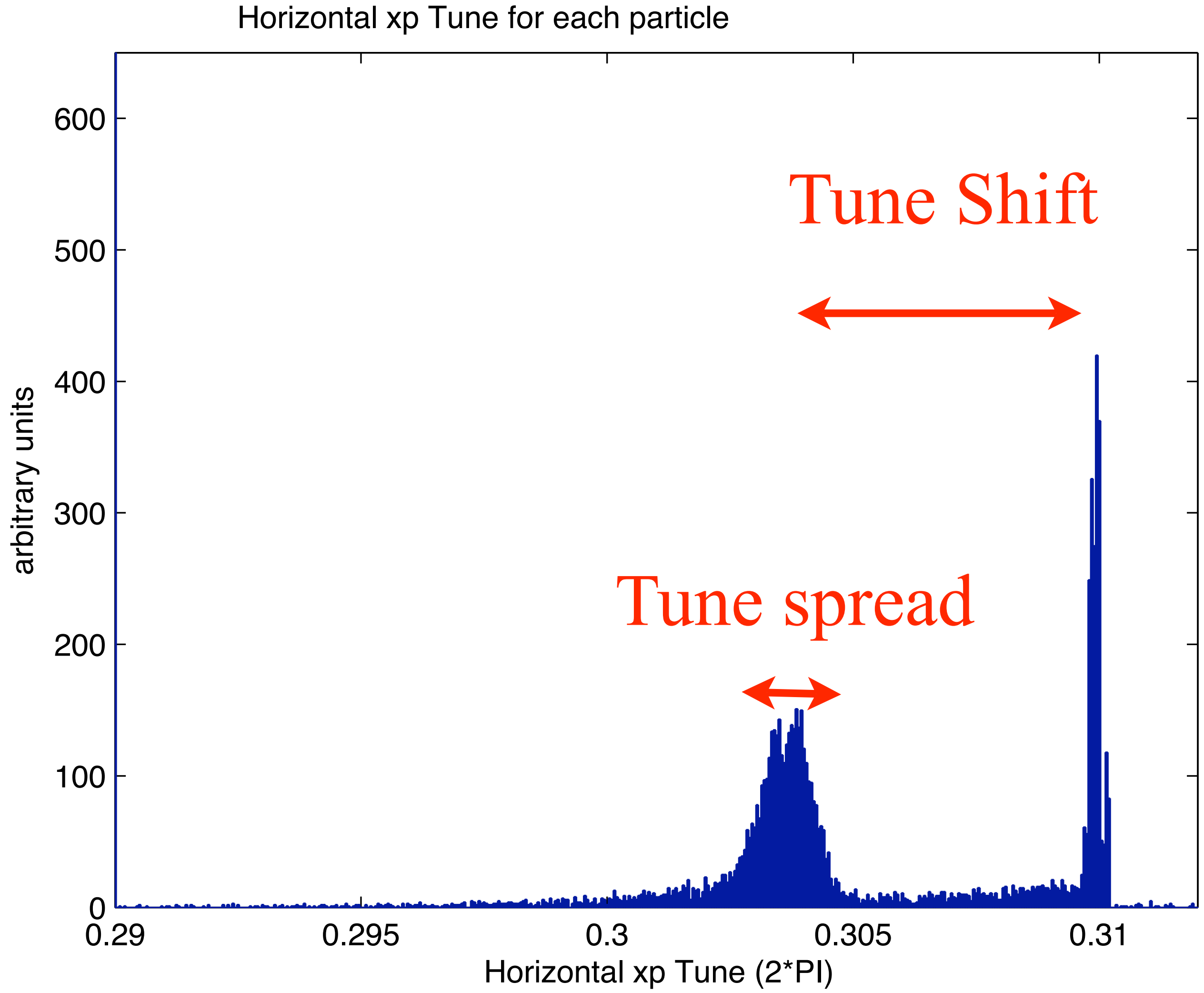
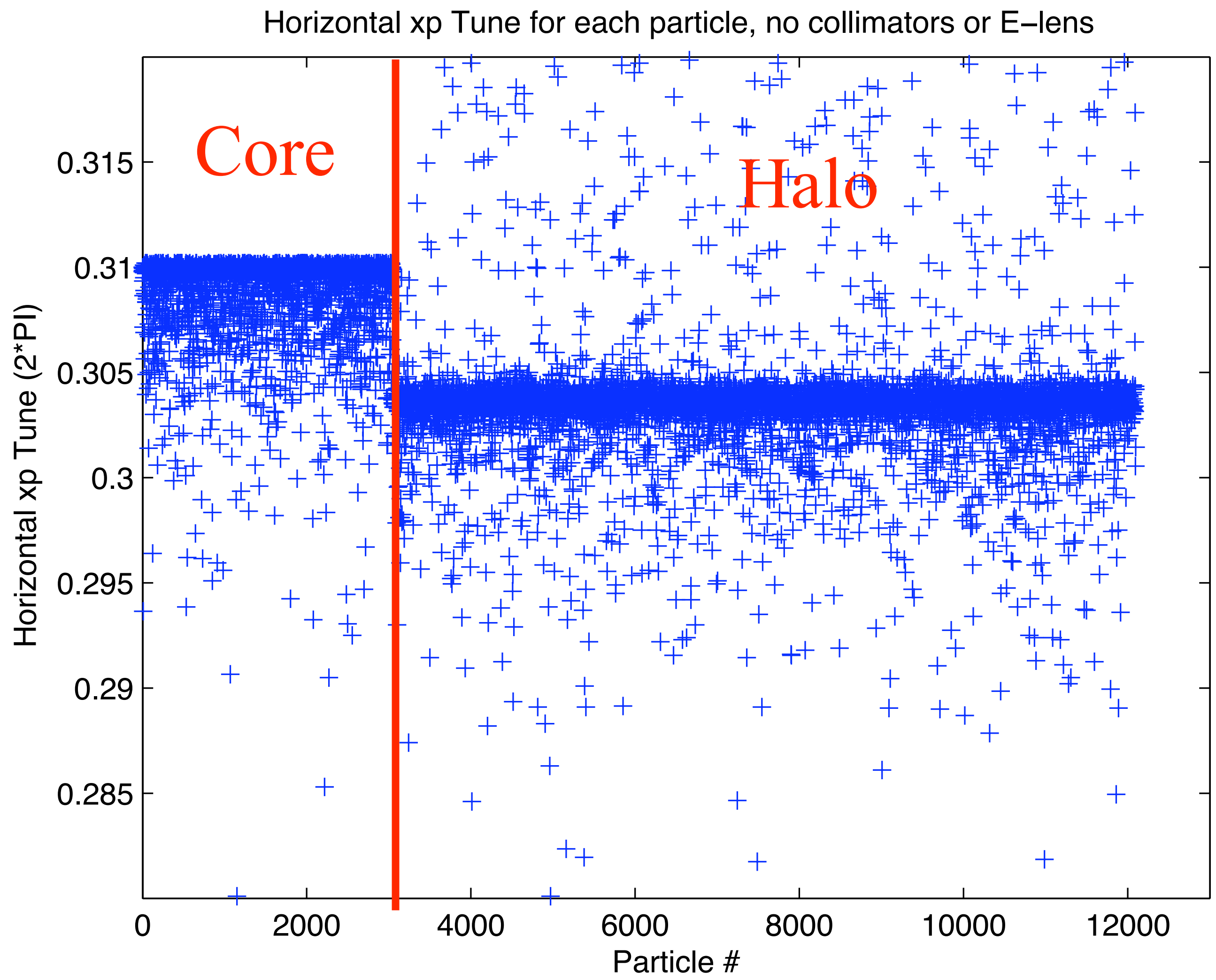
- Tune spread for beam halo is about dQ = 0.001 (agrees with simple tune shift formula)
- Acceptance for resonance condition is about dQ = 0.002 (see previous slide)





- E-lens kick causes tune shift of 0.006 for halo particles
  - Here 2 m long, 50 Amps e-lens
- Studies with AC Current and Gaussian Beam ongoing...
- Can we tune shift with a DC e-lens to a lattice resonance?

Practicalities in E-lens Construction

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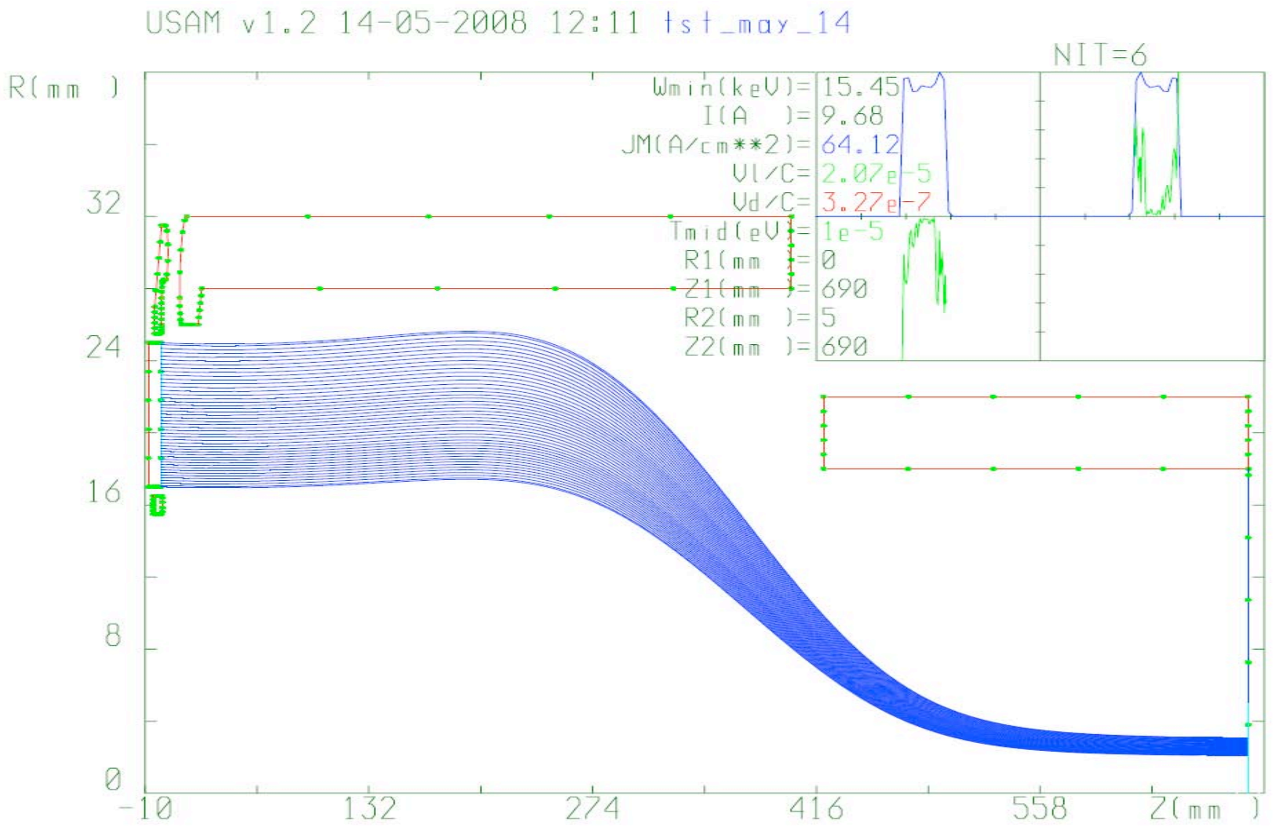
- Electron lenses have been used for some time at Fermilab (Tevatron Electron Lens: TEL)
- The basic E-lens parameters for collimation are similar to those for the TELs already built
- Magnetic and vacuum systems cary over in design
- Required R&D on hollow electron gun and driver
  - Hollow electron beam guns are widely used in electron cooling devices
- R&D studies on gun already begun
  - Here is an simulation of a hollow electron gun with magnetic compression provided by two solenoids



Future work

- Simulation studies:
    - AC Current Studies
    - Use a different bunch distribution.
    - Use a more realistic Electron Lens
        - Errors
            - Effects of small deviations of the electron beam trajectory from straight line
            - Field leaking into beam core
        - Realistic Gaussian shape to electron beam
    - Parametric study
  - Look at local cleaning efficiency with electron lens added
    - Up to now just looking at evolution of beam profile
- Impedance contribution of E-lens
- Similar devices exist, but R&D work for specific modifications
  - Hollow E-beam gun must be developed
  - R&D plan has been devised for LHC electron lens

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Current Conclusions

- A realistic hollow electron lens has been simulated to remove the beam halo in the LHC down to 3 sigma within 1500 turns.
- Large Beta is best such as at BBC locations, but still possible at TCHS collimator locations
- Cleaning efficiency may improve but must be studied
- Incorporating an electron lens may allow for the pulling of the primary and secondary collimators to larger sigma without sacrificing cleaning efficiency
- AC current has been simulated to improve the cleaning time for single on-tune particles.
  - The halo tune spread appears to be small enough for resonant cleaning of a realistic beam.
- A hollow e-lens is very doable and has the potential the improve the LHC collimation system dramatically while requiring few resources.
  - A project plan has been written

Thanks to:

- Vladmir Shiltsev, Shasha Drozhdin, V. Kuznetsov, L. Vorobiev and Alex Valishev
- Ralph Assmann and Valentina Previtali for recommending this project to me.